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TUBE WASTAGE IN FBC BOILERS AT SUMMERSIDE - CAUSES AND RESOLUTION

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TUBE WASTAGE IN FBC BOILERS AT SUMMERSIDE - CAUSES AND RESOLUTION

by

V.V. Razbin* and F.D. Friedrich**

ABSTRACT

Canada's first application of fluidized bed technology to the combustion of coal was a heating plant, completed late in 1982, at Canadian Forces Base Summerside, Prince Edward Island. The plant consists of two bubbling bed boilers, rated at 18,000 kg/h of medium pressure steam, and fired with high sulphur coal, usually supplied from Cape Breton.

Although startup problems were numerous, by the end of the first two heating seasons the boilers had met all guarantees concerning capacity, efficiency and emissions. However, wastage of the heat exchange surfaces exposed to the bed had become evident by the second month of operation. Several corrective measures were implemented with varying degrees of success. Modifications to the distributor plate to change the solids flow pattern simply changed the location of wastage. Installation of refractory impaired boiler performance, and wastage continued elsewhere. Ultimately, two configurations of protective hardware were found to be effective; closely-spaced pin studs on the waterwalls, and longitudinal rods, five per tube, on the inbed tubes.

This paper provides data on the metal wastage in the Summerside boilers, organized chronologically with the major measures taken to prevent erosion. Effects of air jets, large particles, location of inbed tube bundles and several forms of protective hardware are discussed. Also described is a current experiment with the inbed tube bundle, which involves an alloy, two types of protective hardware, and a change in tube bundle configuration.

Since the fall of 1985 the boilers have been operating successfully with no significant tube wastage.

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DÉGRADATION DES TUBES DE CHAUDIÈRES À LIT FLUIDISÉ, À SUMMERSIDE CAUSES DU PROBLÈME ET SOLUTION

par

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RÉSUMÉ

La technique de combustion en lit fluidisé a été appliquée à la combustion du charbon pour la première fois au Canada à la centrale thermique de la base des Forces armées canadiennes dont la construction a été complétée vers la fin de l'année 1982, à Summerside, Ile-du-Prince-Edouard. L'installation comprend deux chaudières à lit fluidisé à bulles ayant une puissance nominale de vapeur sous pression moyenne de 18 000 kg/h. Elles sont alimentées avec du charbon à haute teneur en soufre provenant habituellement du Cap-Breton.

Bien qu'au départ les problèmes aient été nombreux, à la fin des deux premières saisons, les chaudières en service ont répondu à tous les critères relatifs au rendement, à l'efficacité, et au contôle des émissions nocives. Cependant, au cours du deuxième mois, il est devenu évident que les surfaces de l'échangeur de chaleur exposées au lit commençaient à subir les effets de la corrosion. Plusieurs mesures qui avaient été prises en vue de corriger la situation ont eu un succès mitigé. Les modifications apportées à la plaque de distribution en vue de modifier le schéma d'écoulement des solides ont simplement déplacé le problème. La chaudière dont le système réfractaire était défectueux a continué de donner un rendement médiocre et les effets de l'érosion se sont fait sentir ailleurs. Finalement, deux formes de protection ont donné de bons résultats; la fixation de goujons à peu de distance les uns des autres sur les écrans d'eau et de tiges longitudinales, à raison de cinq par tube, sur les tubes incorporés au lit.

Dans le présent rapport, les données sur l'érosion des tubes des chaudières à lit fluidisé, à Summerside, sont présentées en ordre

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chronologique de même que les mesures principales prises en vue de prévenir les dommages. Les effets des jets d'air, des particules de grande dimension, de l'emplacement des faisceaux tubulaires ainsi qui plusieurs sortes de matériaux de protection sont étudiés. Le document fait également état d'un essai en cours portant sur les faisceaux tubulaires et qui comprend l'étude d'un alliage, de deux genres de matériaux de protection et d'une modification de la structure du faisceau tubulaire. Depuis l'automne 1985, les chaudières ont fonctionné de façon adéquate et les effets de l'érosion ont été minimes.

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INTRODUCTION

In November 1982 construction was completed on Canada's first coal-fired fluidized bed heating plant. The demonstration project was co-funded by the Canadian government's departments of National Defence (DND) and Energy, Mines and Resources (EMR). The plant is located at Summerside, Prince Edward Island, and consists of two atmospheric fluidized bed combustor (AFBC) boilers, each rated at 18000 kg/h (40000 lb/h) of medium-pressure steam.

The main objectives in funding a full-scale AFBC plant were to demonstrate, evaluate and gain first-hand operating experience with a technology that provides environmentally benign utilization of high sulphur coal, and to expedite the acquisition of FBC boiler capability by Canadian boiler suppliers.

As might be expected with the first full-scale application of a new technology, a variety of operational problems were encountered during the first few heating seasons. Some were related to the fluidized bed and others were not. Chief in the former category was wastage of the waterwall and inbed tubes by erosion. The manifestations of and the solutions to those problems are the primary focus of this paper.

Notwithstanding some very serious engineering problems the AFBC boilers at Summerside are now considered to be fully satisfactory in all major respects. All guarantees concerning capacity, efficiency and emissions control have been met. Furthermore, operational problems affecting reliability and availability have been resolved to the extent that these boilers are as dependable and easy to operate as any other type of coal-fired boiler. Tube wastage appears to be resolved or at least under control. Quantitative predictions will require some years of further operating experience, but it seems likely that protective hardware installed in the boilers can prolong the life of the pressure parts indefinitely.

BOILER DESIGN

The following description applies to the boilers at the time of construction, and primarily addresses those features essential to an understanding of the tube wastage phenomenon. Modifications made

subsequently are described later, in chronological order. More complete descriptions of the Summerside FBC heating plant are given elsewhere (1,2).

The boilers were supplied by Foster Wheeler Limited as shop fabricated packages based on a conventional two-drum watertube design with natural circulation throughout. As shown in Fig. 1, the furnace comprises two fluidized beds arranged parallel to the convection bank and contained by vertical membrane waterwalls.

Bed A, next to the convection bank, is the preferential bed in that it is intended for use whenever the boiler is in operation. It is equipped with an oil fired light-up burner and it receives all the recycle material from the boiler bank hopper and a downstream cyclone. It is sized to produce about 40% MCR. Dimensions are 1.23 m x 2.88 m (4 ft x 9.5 ft).

Bed B, also known as the secondary bed, is the same length but slightly wider than Bed A - 1.39 m (4.5 ft) and is intended to operate with Bed A at loads above 40% MCR. In addition to the waterwall enclosure there is a bank of 18 evaporator tubes. The size of the inbed tubes within the expanded bed height is 57.15 mm (2.25 in.) OD. These tubes are inclined at 30° to the horizontal, to facilitate natural circulation. To forestall metal wastage difficulties a substantial wall thickness of 7.5 mm (0.296 in.) was selected for the submerged portion of the inbed tubes. That portion was furthermore covered with a so-called "alonized" layer. The rest of the inbed tubes in the freeboard and the waterwall tubes are 50.8 mm OD x 4.3 mm (2 in. OD x 0.169 in.) wall thickness without protection against metal wastage.

Analytical data for the two coal types, which formed the bulk of the fuel supply, are given in Tables 1 and 2. Coal is fed to each bed by a spreader stoker located in the front wall and thus throws coal parallel to the long axis of each bed. The coal size, as fired, is 31.8 mm x 0 (1.25 in. x 0). The units are also capable of burning wood chips.

Limestone is introduced via a drop pipe into the end of each bed opposite the coal stoker. Each bed is equipped with a drain pipe located at the stoker end. This arrangement provides maximum residence time for the fresh limestone as well as for the large coal or ash particles, which the stokers are likely to throw farthest. Five aeration nozzles are located around the inlet to each bed drain pipe to ensure fluidization in that

region and hence free flow of bed material into the drain. The arrangement is shown schematically in Fig. 2.

The distributor plates are uncooled and are penetrated by a large number of alloy steel T-shaped 6.4 mm (0.25 in.) nozzles or bubble caps, through which air is introduced for combustion and fluidization. The nozzles project about 100 mm (4 in.) above the distributor plates, thereby leaving a layer of undisturbed bed material as insulation. Originally, Beds A and B contained 142 and 242 nozzles respectively. Additional T-shaped alloy steel as well as large diameter - 31.8 mm (1.25 in.) stainless steel nozzles were added subsequently as detailed later. Figure 3 shows the two types of nozzles.

To improve the efficiency of both combustion and sulphur capture, fly ash from the convection bank hoppers and from the cyclone dust collector is recycled into Bed A. Initially, the boiler bank reinjection system consisted of two conventional pneumatic eductors supplied with medium pressure air from a positive displacement blower. The cyclone recycle system consisted of a set of double gate valves and transfer hoppers with pneumatic transport to two ports at the boiler drum wall of Bed A. Thus, the entire reinjection system for one boiler consisted of two eductors, one double lock hopper system, two blowers, four reinjection ports and associated piping and controls. The whole system was progressively modified and only the boiler bank reinjection blower and the four openings formed by the furnace wall tubes in Bed A of each boiler were unchanged. Additional details of boiler design are given in Table 3.

OPERATIONAL HISTORY

1982/83 HEATING SEASON

Both boilers were boiled-out in late November 1982. Commissioning activities then focussed on Boiler 1, which was first fired on December 12, 1982, but due to difficulties documented elsewhere (2), was shut down the next day. It was subsequently operated from January 19 to 23 and from February 1 to 8, 1983.

An inspection of Bed A on January 29, 1983 revealed evidence of polishing of the waterwall tubes on the drum side of the bed. It was observed that in a few places the upper faces of tube field welds were

polished, which indicated a predominantly downward flow of bed material at the wall. However, the tube thickness measurements indicated greater metal wastage below the welds than above. Other observations were:

- polishing appeared to be restricted to a horizontal band around the walls ranging from 600 to 1200 mm (24 to 48 in.) above the distributor plate,
- the stainless steel reinjection nozzles, which originally projected into the bed, were also polished, and
- some refractory below the stokers and around the ignition burner had come off the tubes.

Two remedies were implemented in both boilers. First, to counter the downward flow of bed material near the walls, eighteen 6.4 mm (0.25 in.) alloy steel nozzles per bed, projecting 203 mm (8 in.) above the distributor plate, were installed around the periphery of the distributor plates. In Bed B, however, six large - 31.8 mm (1.25 in.) OD - T-shaped stainless steel pipes were fabricated and installed below the inbed tubes. Their size, relative to the standard nozzles, is shown in Fig. 3. Second, a belt of Lavalox refractory, 5 mm (2 in.) thick, extending from 600 to 1200 mm (24 to 48 in.) above the distributor plate, was installed on all membrane walls as shown in Fig. 4.

Tube thickness measurements were carried out in both boilers. When the foregoing modifications were made, Boiler 2 had not yet been operated. It was subsequently operated for 997 h to the end of 1982/83 heating season as recorded in Table 4. During this heating season, Boiler 1 was fired with Evans coal whereas Boiler 2 was fired partly with Evans and partly with Devco coals.

1983/84 HEATING SEASON

Boilers 1 and 2 were operated for about 2450 and 1840 h respectively. The fuel was mainly Brogan coal. Frequent shutdowns due to other causes provided ample opportunity for regular monitoring of the boiler tubes and therefore of the effectiveness of the measures implemented in the previous heating season. The Lavalox refractory satisfactorily protected the heating surfaces it covered. The maintenance, however, was excessive. In February 1984 almost all the refractory in Bed A of Boiler 2 had to be replaced. This was attributed to faulty refractory material.

Furthermore, it was observed that tube wastage occurred below the refractory belt and at a high rate. Figure 5 shows contour plots of wall tube thickness for one wall measured over three years. Plots for the other walls show similar patterns. Inbed tubes also showed polishing even though they had only one-third to one-half of the total operating hours of each boiler. Substantial spalling of the alonized layer as well as polishing of the underside of the tubes near the lower bend were evident. Measurements indicated a maximum metal loss of about 1 mm (0.039 in.).

The metal wastage below the refractory belt was addressed by welding four rows of sheds, mad of alloy flat stock, scalloped to accommodate the wall tubes and inclined downwards at 45°, as shown in Fig. 4. This approach was chosen over the application of more refractory to avoid further deterioration of the heat transfer characteristics of the fluidized beds. The work was carried out in August 1984.

1984/85 HEATING SEASON

Boilers 1 and 2 were operated for 2600 and 2800 h respectively. Table 4 shows the breakdown for each bed. The fuel used was Evans coal.

The sheds installed below the refractory belt proved to be ineffective in protecting the tubes. As shown on the third set of contour plots in Fig. 5, wastage continued between the sheds. Some segments of the sheds were lost through wear of the welds which attached them to the waterwall tubes. An area not covered by the sheds also showed significant tube wastage.

In February 1985 a tube failure occurred in Bed A in Boiler 2 at the bend below the burner opening and approximately 550 mm (21 in.) above the distributor plate. The refractory and the sheds that originally covered this tube were missing. Adjacent tubes were also substantially thinned, therefore a section of six tubes that formed the burner opening was replaced. The replaced area was covered with Lavalox refractory.

The tube failure dramatically underscored what a regular program of tube thickness measurements and boiler performance tests was already revealing: that of all the measures implemented so far only the Lavalox on the waterwalls was protecting the tubes. However, although protecting the tubes, the Lavalox was impairing boiler performance in terms of heat transfer to the walls. Consequently, high excess air was required to

control bed temperature, leading to high elutriation rates from the bed, which overloaded the fly ash reinjection system and the baghouse. Alternative means for protecting the tubes were needed.

EXTENT OF WASTAGE - SUMMER OF 1985

A. Waterwall Tubes

A representative view of waterwall wastage is shown in Fig. 5 to 8, in which contour plots of tube wall thickness are given for each of the four walls of Bed A in Boiler 2. In terms of complete sets of measurements taken at identical time intervals, the database is not complete, but it does provide sufficient information to identify the following trends:

- On the drum and partition walls the wastage patterns were essentially similar. A maximum rate of metal loss of about 0.40 mm (0.016 in.) per 1000 h (over the first 3200 h of operation) was concentrated just under the belt of Lavalox refractory, with a subsequent rate of metal loss of 0.04 mm (0.002 in.) per 1000 h (over the succeeding 2400 h of operation) with the protective sheds in place.
- On the stoker wall, there appeared to be negligible metal loss in the first 2000 h of operation.
- On the sorbent injection wall, after 5300 h of operation, a general rate of metal loss of about 0.20 mm (0.007 in.) per 1000 h, was concentrated just below the refractory belt. There was also a localized area with a rate of 0.34 mm (0.013 in.) per 1000 h of operation. The sorbent injection wall appeared to be more severely attacked than the stoker wall, although no direct comparison is possible.

B. Inbed Tubes

By the summer of 1985, the inbed tubes in Boilers 1 and 2 had accumulated 3770 h and 3220 h of service respectively. This is about half the total operating time of each boiler. Tube wastage data reported here are representative of the tube conditions up to summer 1985 even though the inbed tubes were in the boilers during the 1985/86 heating season. This is because, as will be explained in more detail, protective hardware applied to the inbed tubes in the summer of 1985 was sufficiently effective that all the tubes, when removed in the summer of 1986, had a thin carbonaceous deposit with no signs of polishing on the parent tube metal.

Thus, in the summer of 1986, all 36 inbed tubes were removed and each tube was sectioned at four locations as shown in Fig. 9. The wall thickness of each section was measured at 45° intervals, eight in all. Measurements for one particular tube are shown in Fig. 10, while the maximum and average metal wastage rates for each tube are given in Table 5. The maximum and average wastage rates for the tubes in Boiler 1 are also shown graphically in Fig. 11. Boiler 2 exhibits similar wastage patterns.

Additional data are given in Fig. 12 to 15 which, for each boiler, show contour and grey map representations of tube wastage in the most severely affected areas, i.e., the bottom 90° segment of the tubes. The gray maps were plotted on the assumption that wastage progressed linearly from one section to the next and from one tube to the next. The numbering sequence applied to the tubes is such that for Boiler 1 the bed drain is in the vicinity of tube 18, whereas for Boiler 2 the bed drain is in the vicinity of tube 1. It is immediately clear from the grey maps that tube wastage is highest at the ends of the beds, with the most severe wastage being near the bed drains.

FURNACE MODIFICATIONS - SUMMER 1985

Having concluded that neither the application of refractory and sheds to the waterwalls nor the alonized coating on the inbed tubes provided satisfactory protection against tube wastage, EMR and DND, after consultation with the operating personnel at the Georgetown FBC unit, opted to implement alternative measures that appeared to be effective at Georgetown.

Thus, during the summer of 1985, the Lavalox refractory and the sheds were removed from the waterwalls and replaced with carbon steel pin studs installed on the tubes from the level of the distributor plates to a height of about 1525 mm (5 ft), i.e. slightly higher than the expanded bed height. The studs, 9.5 mm diameter x 19 mm long (0.37 x 0.75 in.), were applied with a stud-welding gun. The spacing was determined by the tip of the gun and was about 24.5 mm (1 in.) centre to centre on a staggered pitch. Figure 16 shows the arrangement. Special attention was paid to areas of change in geometry, such as burner openings or reinjection ports, where local turbulence contributes to metal wastage. Such areas were

protected by installing refractory over the studs. All ceramic insulators used during the studding were subsequently broken to ensure maximum heat transfer to the walls. During the studding one tube was penetrated, due to incorrect setting of the voltage to the gun. A short section of tubing had to be replaced.

Following studding of the waterwalls it was decided to protect the inbed tubes by welding longitudinally, to each tube, five 9.5 mm (0.37 in.) diameter carbon steel rods. These were positioned at the 1,4,6,8 and 11 o'clock locations around the tubes as shown in Fig. 17. These locations were determined by the observed wear pattern of the alonized layer on the bare inbed tubes, i.e., substantial polishing in the bottom quadrant and minor polishing at the top. The rods were continuously welded on both sides and were applied to the tubes from the level of the distributor plate to 200 mm (8 in.) beyond the second bend, which is above the expanded bed. Approximately every 150 mm (6 in.) along the tubes, the rods were joined by small crosspieces which served as dams to prevent bed material from streaming up or down the tubes between the rods.

During welding of the rods, several tubes were burned through because the wall thickness had been reduced by about 80%, i.e., from the original 7.5 mm (0.296 in.) to about 1.4 mm (0.055 in.) This was the first clear indication of the severity of wastage of the inbed tubes. Since time did not permit complete replacement of the two inbed tube bundles before the 1985/1986 heating season, only the burned-through sections were replaced. The units were put in service and plans were initiated for complete tube replacement in the summer of 1986.

1985/86 HEATING SEASON

With respect to tube wastage, the 1985/86 heating season was uneventful. Boiler 1 was in service for 2140 h, of which Bed B was in operation for 558 h. Boiler 2 was in service for 4169 h during which Bed B operated for 2541 h.

It was found that the studs provided substantial gains in heat transfer compared to the refractory. Boiler capacity was increased by almost 50%, and in the upper load range it was possible to reduce the excess air required for control of bed temperature from the 9 to 11% O_2 range down to 5 to 6% O_2.

Boiler 2 was inspected after 2500 h of operation following the application of the studs and the rods. No sign of polishing on any of the waterwall tubes was revealed. Instead, the tubes were covered with a thin, black carbonaceous deposit. Some studs had rounded tips whereas others were capped with a partially sintered deposit of ash or shale. Substantial quantities of gravel-sized shale particles were trapped between the studs in a band 350 to 900 mm (14 to 35 in.) above the distributor plate. The inbed tubes showed some polishing of the rods but metal loss was not measurable and no parent tube metal was affected. There were also carbonaceous deposits on the tubes as described above. A further inspection at the end of the heating season showed conditions were unchanged.

REPLACEMENT OF INBED TUBES - SUMMER 1986

In accordance with plans made the previous year when extensive tube wastage of the inbed tubes became apparent, these tubes were replaced during the 1986 summer shutdown. The new tube bundle is of a different configuration as shown in Fig. 18. The angle of the new tubes was reduced from 30° to 15°, an angle still considered safe for natural circulation. The change in angle was accommodated by extending the vertical portion at the lower bend, so that the tubes are mostly above the expanded bed in the splash zone. Also, to reduce the fluidizing velocity between the tubes, they were staggered in two rows, rather than arranged in a single row as formerly.

In Boiler 1, all 18 tubes are of carbon steel, SA 178 Gr. A. On the basis of the previous year's favourable experience the tubes were installed with rods as shown in Fig. 17. In Boiler 2, three different approaches are being compared. First, six SA 178 Gr. A tubes are protected with longitudinal rods as in Boiler 1. Second, six tubes of the same material are protected with pin studs identical to those that protect the waterwall tubes, arranged in five rows, oriented similarly to the rods as shown in Fig. 19. Third, six tubes are installed without protective hardware but in a T-9 alloy composition, i.e., 8.2% Cr, 0.95% Mo and 0.40% Mn. Primarily for reasons of availability, the alloy tubes are 50 mm OD x 8.6 mm (2 in. OD x 0.340 in.) wall thickness. The carbon steel tubes are 57 mm OD x 7.5 mm (2.25 in. OD x 0.296 in.) wall thickness, the same as the original inbed tubes.

1986/87 HEATING SEASON

The 1986/87 heating season was again uneventful with the boilers operating the following hours:

	Bed A	Bed B
Boiler 1	2987	1301
Boiler 2	2218	1097

At the end of the heating season, the waterwalls were largely blanketed with ash particles and sinter trapped between the studs. The debris was removed by sandblasting whereupon it was observed that the ends of studs in the preferential beds were showing wastage indicative of a flow pattern as that shown in Fig. 20. However, this has not yet proceeded to a measurable shortening of the studs and more operating time is required to clearly identify the patterns. The waterwalls were found to have the same carbonaceous deposits as those of the previous year.

The inbed tubes, with only a little more than 1000 h of service, showed no sign of wastage beyond some polishing of the protective rods. The protective hardware and the welding slag prevent access of an ultrasound probe to the tube for thickness measurement, except at the sides of the tubes where wastage, up to now, has been negligible. It appears that an additional three or four heating seasons will be required to obtain quantitative data on wastage rates. This fact constitutes an encouraging qualitative result.

DISCUSSION

EFFECT OF LARGE AIR JETS

The areas of high wear on the waterwalls, shown in Fig. 5 and 6 correspond fairly well with the location of the large air nozzles installed in 1983 around the periphery of the beds to counteract the perceived downwash of bed material at the wall.

More recently, the studs protecting the waterwall tubes in the preferential bed have shown wear that can be explained by a gulf-stream type of flow pattern as indicated in Fig. 20. In the upper part of the studded wall, the lower edges of the studs are showing wear, whereas in the lower part the upper edges of the studs are wearing. Gulf-streaming, although

not fully understood, may be caused in part by the horizontal air jets from the ash reinjection system. Further operating hours are required to make detailed measurements and draw conclusions.

As for the original inbed tubes, Fig. 12 to 15 show that the highest wastage is over the bed drain pipe. This is caused by a combination of two factors. First, the five aeration nozzles located around the drain pipe undoubtedly increase the fluidizing velocity above it. Second, the fluidizing velocity is further increased by the air supplied from one side of the large 31.8 mm (1.25 in.) diameter T-shaped nozzles located next to the drain pipe. The inbed tubes also exhibit peaks in wastage rate elsewhere in Bed B, which correlate with the positions of the remainder of these large nozzles.

EFFECTS OF LARGE PARTICLES

Other zones of high wastage, second in significance only to the inbed tubes at the bed drain region, are the sorbent injection walls. A comparison of Fig. 7 and 8, even allowing for the difference in operating time, shows the difference in severity of the attack on the waterwalls. A similar pattern holds for the inbed tubes. Figures 12 to 15 show high wastage near the sorbent injection end of the beds, i.e., for Boiler 1 at tube No. 18; for Boiler 2 at tube No. 1.

The cause appears to be an accumulation of large particles in these regions of the bed and this fact was repeatedly observed during shutdowns. This is not surprising since bubbling fluidized beds are not noted for good lateral mixing. This region, which is located farthest from the coal stoker and from the bed drain pipe, accumulates the large shale and ash particles, about 30 mm (1.2 in.) diameter, occurring in the coal and thrown by the stokers. Also, limestone is introduced at the same location and the oversized particles tend to stay in this area. During normal operation the large particles impinge on the heating surfaces with considerable momentum, causing high rates of metal loss.

LOCATION OF INBED TUBE BUNDLES

Examination of the original inbed tubes showed that, aside from the areas of higher attack at the two ends of the bed, tube wastage was more severe along the centreline (longitudinal axis) of Bed B and less severe

near the partition and the front walls where the two bends of the tube bundle are located. The region of higher metal wastage corresponds to that portion of the inbed tubes passing through the upper half of the expanded bed. This can be explained by the higher particle velocities which prevail due to bubble coalescence and acceleration at this bed height. Tube wastage studies of evaporator surfaces by others (3) indicate that lower wastage occurs in the lower parts of the bed where velocities are more uniform. Lower rates will also exist in the splash zone above the bed where particle concentrations are reduced.

EFFECT OF PROTECTIVE HARDWARE

In the three heating seasons prior to studding of the waterwalls in 1985, the preferential beds in both boilers each operated for about 5650 h. Despite the various measures employed up to that time, many areas had suffered wastage of more than 1 mm (0.040 in.) or 25% of the original wall thickness. Studding was then applied to the damaged surfaces and in the following two heating seasons Boilers 1 and 2 operated for 5129 h and 6387 h respectively. Although ultrasound thickness measurements of the tubes are now impossible due to the presence of the studs, no further wastage or even polishing of the parent waterwall tubes were indicated. Some metal loss on the free ends of the studs occurred but not enough that shortening of the studs can be accurately determined. It appears that about five years of operation will be required before stud life can be predicted with any reliability. This fact in itself is a favourable indication of their effectiveness in preventing tube wastage.

The operating time, in hours, of the inbed tubes is summarized as follows:

	Boiler 1	Boiler 2
Original tubes, prior to application of rods	3771	3222
Original tubes with rods, 1985/86 heating season	558	2541
New tube bundle, 1986/87 heating season	1301	1097

Prior to the application of the rods the inbed tubes suffered severe metal wastage that, in a few localized areas, reduced the wall thickness from 7.5 mm (0.296 in.) to 1.4 mm (0.055 in.) The best evidence of the effectiveness of the rods is that these same tubes, thus protected, operated without failure or any measurable wear of the rods throughout the

1985/86 heating season. For Boiler 2, that amounted to 2541 h or 79% of the previous time in service. To date, the new tube bundles have seen only limited service. No signs of deterioration were evident at the end of the 1986/87 heating season and it appears that a few thousand hours of further operation will be required to assess metal wastage rates.

ONGOING STUDIES AT SUMMERSIDE

The two fluidized bed boilers at Summerside are now in routine operation as the main source of steam for space heating. Numerous modifications have been made to improve operation and performance, and confidence in their reliability has been established by two successive heating seasons of fairly trouble-free operation. Because of this, and the good turndown capability of the units, plant staff started the 1987/88 heating season by bringing one fluidized bed boiler into service, rather than one of the older, smaller stoker-fired units, which previously carried the light loads at the beginning and end of each season.

CANMET has completed its program of combustion performance demonstration, although most of the data are still unpublished. Ongoing studies consist of:

a) monitoring general plant performance, particularly with respect to systems which have been substantially modified, such as the fly ash reinjection systems,
b) annual inspection of the studded waterwalls, and
c) periodic inspection of the new inbed tube bundle.

These new tube banks offer the potential to explore several factors related to metal wastage; the resistance of T-9 alloy, the effect of changing the slope of the tube from 30° to 15°, rods versus studs, the merits of staggered versus in-line layout and as well, the effect on boiler performance of having the bundle mostly above the expanded bed. It is expected that about 5000 h (about four heating seasons) of operation with Bed B will be required to obtain definitive results.

CONCLUSIONS

To minimize tube wastage fluidization in the bed should be as uniform as possible. Large air jets, such as those often used for pneumatic ash reinjection or to facilitate bed drain, should and can be avoided through appropriate design. To minimize fluidizing velocity, the bed should have sufficient heat transfer surface to control bed temperature rather than employing excess air.

Because large particles accelerate wastage, the top size of the fuel should probably be limited to 19 mm (0.75 in.) or less for overbed feeding, or beds should be designed to minimize the residence time of large particles. This can be accomplished by using directional nozzles, by appropriate sloping of the distributor plate, or by providing more bed drain locations.

Tube bundles should be kept out of the upper half of the expanded bed to avoid the higher wastage rates associated with the higher bubble velocities. Alternative locations are in the lower half of the bed or in the splash zone. The latter is now being tested at Summerside.

Pin studs have been shown to be effective in preventing tube wastage of the waterwalls. Likewise, longitudinal rods, correctly spaced and positioned, have been found effective in preventing wastage of the inbed surfaces.

Studies are continuing at Summerside to explore the resistance to tube metal wastage of:

1) inbed tubes fabricated in T-9 alloy,
2) tubes protected by pinstuds instead of rods, and
3) different configuration and location of the inbed tube bundle within the combustor.

REFERENCES

1. Taylor, M.E.D. and Friedrich, F.D. "The CFB Summerside Project. Canadian state of the art in AFBC boilers" Division Report ERP/ERL 82-10, Energy Research Laboratories, CANMET, Energy, Mines and Resources Canada, Ottawa, Ontario, Canada, 1982.

2. "Engineering evaluation of fluidized bed boiler demonstration at CFB Summerside, Prince Edward Island" Prepared by Monenco Consultants Ltd. for CANMET, Energy, Mines and Resources Canada, Ottawa, Ontario, Canada. DSS Contract Serial No. OSQ85-00343.

3. "Update on in-bed tube wastage in the TVA 20 MW fluidized-bed combustor" DOE Newsletter Number 69, August 1, 1987 DOE/FE-0069/69.

Table 1 - Analytical data for Evans and Brogan coals*

Product name		Evans Coal Stoker Pea			Brogan Coal Channel Sample		
Screen opening, mm²		19 x 6.4					
ERL number		3185-84			3362-84		
Rank of coal		High-volatile B bituminous			High-volatile A bituminous		
Proximate analysis:		As Rec'd	Dry	Dry Ash Free	As Rec'd	Dry	Dry Ash Free
Equilibrium moisture	%	6.87			11.15		
Ash	%	11.38	12.22		6.02	6.77	
Volatile	%	32.85	35.28	40.19	32.31	36.36	39.00
Fixed carbon	%	48.90	52.50	59.81	50.53	56.87	61.00
Ultimate:							
Carbon	%	63.53	68.22	77.72	65.33	73.52	78.86
Hydrogen	%	4.07	4.37	4.98	3.53	3.97	4.26
Sulphur (Pyritic)	%	(3.37)	(3.62)	-	(2.95)	(3.32)	-
(Sulphate)	%	(0.23)	(0.25)	-	(0.25)	(0.28)	-
(Organic)	%	(2.52)	(2.70)	(3.08)	(1.00)	(1.13)	(1.21)
Total	%	6.12	6.57	-	4.20	4.73	-
Nitrogen	%	1.29	1.38	1.57	1.93	2.17	2.33
Ash	%	11.38	12.22	-	6.02	6.77	-
Oxygen, by difference	%	6.74	7.24	8.25	7.85	8.84	9.48
Heating value:	MJ/kg	27.58	29.61	33.73	28.11	31.63	33.93
	kcal/kg	6587	7073	8057	6714	7556	8105
	Btu/lb	11856	12731	14503	12085	13601	14588
Hardgrove grindability index		54			54		
Free swelling index		3.0			5.0		
Ash Fusibility temperature		Reducing	Oxidizing		Reducing	Oxidizing	
Initial	°C	1021	1368		1096	1449	
Spherical	°C	1032	1429		1107	1460	
Hemispherical	°C	1163	1435		1110	1466	
Fluid	°C	1202	1446		1121	1468	

* Bonnell, G.W. and Janke, L.C. "Analysis Directory of Canadian Commercial Coals: Supplement No. 6" CANMET Report No. 85-11E; Energy, Mines and Resources Canada, Ottawa, Ontario, March 1986.

Table 2 - Ash analyses for Evans and Brogan Coals*

Product name	Evans Coal Stoker Pea	Brogan Coal Channel Sample
Screen opening, mm^2	19 x 6.4	
ERL number	3185-84	3362-84
Ash analysis, %		
SiO_2	29.10	17.09
Al_2O_3	12.58	8.06
Fe_2O_3	43.41	68.67
Mn_3O_4	-	-
TiO_2	0.57	0.27
P_2O_5	0.50	-
CaO	4.04	0.94
MgO	0.58	0.60
SO_3	4.15	1.37
Na_2O	1.43	0.13
K_2O	1.45	0.81
SrO	-	-
BaO	0.03	-
Loss on fusion	0.27	0.66
Volatile trace element analysis µg/g (ppm)		
Hg	0.13	0.10
Cl	2960	190
F	56.	23.

* Bonnell, G.W. and Janke, L.C. "Analysis Directory of Canadian Commercial Coals: Supplement No. 6"; CANMET Report No. 85-11E; Energy, Mines and Resources Canada, Ottawa, Ontario, March 1986.

Table 3 - Supplier's predicted performance data, 1 boiler at 100% MCR, for the fluidized bed boilers at Summerside

Steam flow	kg/h	18,150
Outlet pressure	kPa	965
Outlet temperature	°C	182
Feedwater temperature	°C	105
Boiler blowdown rate	kg/h	250
Coal feed rate	kg/h	2,210
Limestone feed rate	kg/h	1,019
Combustion air flow	kg/h	21,150
Total air side loss	mm H_2O	1,455
Total gas side loss	mm H_2O	310
Particulate emissions	kg/10^6k.cal	0.216
SO_2 emissions	kg/10^6k.cal	2.52
NO_x emissions	kg/10^6k.cal	2.16
Stack temperature	°C	176
Boiler efficiency (ASME)	%	81.6
F.D. Fan H.P.		221
I.D. Fan H.P.		92.8
Excess air	%	22
Bed dimensions	m	Bed A: 1.23 x 2.88 Bed B: 1.39 x 2.88
Operating temperature	°C	885
Fluidizing velocity	m/sec	2.4
Ca/S ratio		3:1
Expanded depth	m	1.37
Turndown ratio		4.5:1

Table 4 - Summary of operating hours for the FBC boiler plant at Summerside

Date	Boiler 1		Boiler 2	
Up to	Bed A	Bed B	Bed A	Bed B
June 83	619	43	997	192
June 84	3072	1700	2833	1053
June 85	5678	3771	5631	3222
June 86	7818	4329	9800	5763
June 87	10807	5630	12018	6860

Table 5 - In-bed tube erosion rates of Summerside FBC boilers

Tube No.	Boiler 1				Boiler 2			
	Section No.	Location	Erosion rate mm/1000 h		Section No.	Location	Erosion rate mm/1000 h	
			Maximum	Average			Maximum	Average
1	3	8	0.477	0.292	1	2	0.372	0.199
2	1	6	1.220	0.345	2	4	0.776	0.310
3	3	6	0.716	0.220	2	6	0.993	0.403
4	3	6	1.061	0.371	3	6	0.466	0.403
5	3	6	0.769	0.318	3	6	0.341	0.180
6	3	6	0.689	0.291	2	6	0.466	0.196
7	2	6	0.902	0.345	2	6	0.466	0.282
8	3	6	0.663	0.239	2	8	0.466	0.149
9	2	6	0.636	0.252	4	4	0.372	0.183
10	3	6	0.743	0.265	4	8	0.310	0.164
11	2	6	0.636	0.241	1	12	0.248	0.118
12	2	6	0.477	0.254	4	6	0.248	0.112
13	3	6	0.530	0.249	2	6	0.341	0.136
14	3	6	0.504	0.220	3	6	0.186	0.100
15	3	6	1.008	0.292	2	6	0.310	0.118
16	2	6	1.644	0.424	2	6	0.621	0.230
17	2	6	1.644	0.424	2	6	0.776	0.258
18	3	4	0.477	0.199	1	12	0.341	0.164

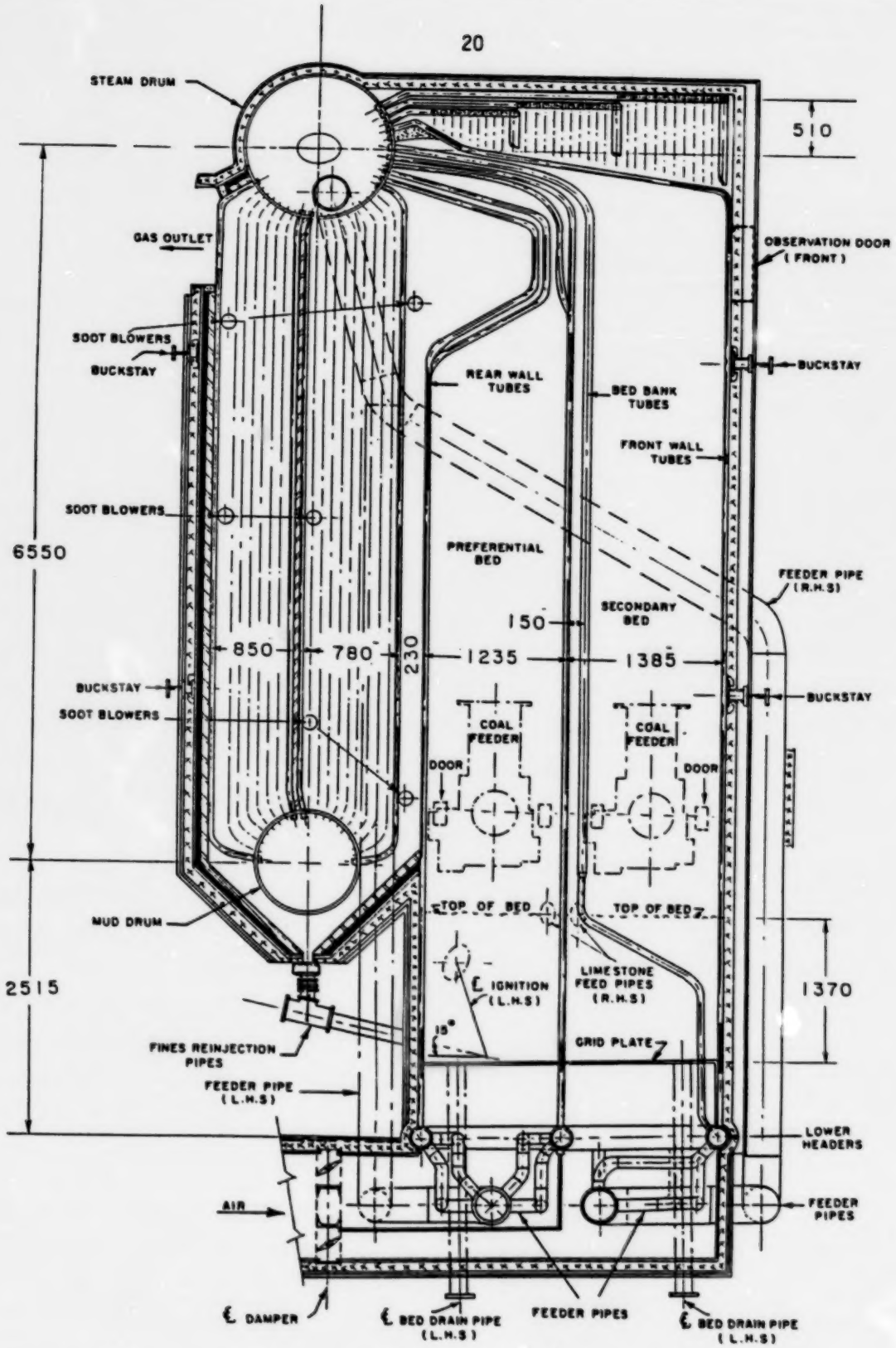


Fig. 1 - Section view of the fluidized bed boilers at CFB Summerside

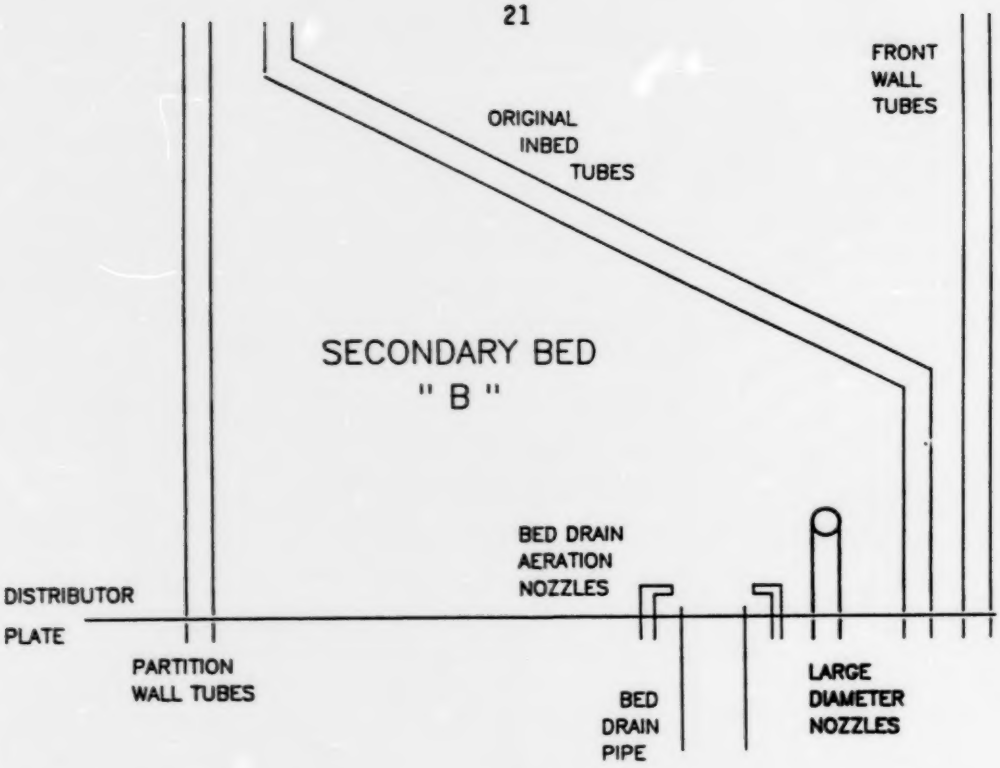


Fig. 2 - Section view of secondary Bed B showing major features

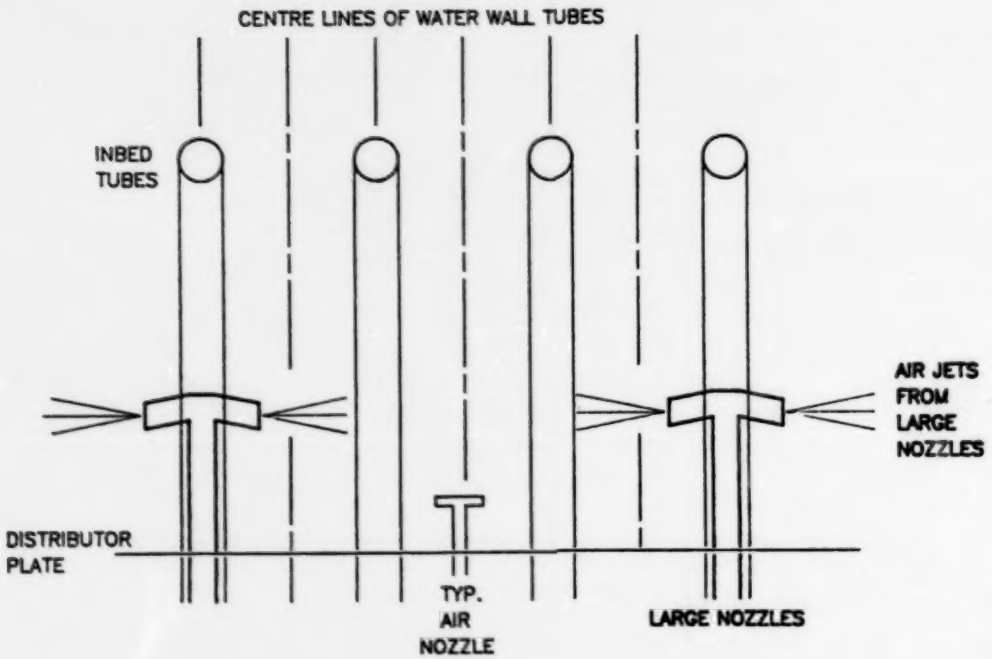


Fig. 3 - Arrangement of inbed tubes, waterwall tubes and retrofitted large nozzles in the FBC boilers

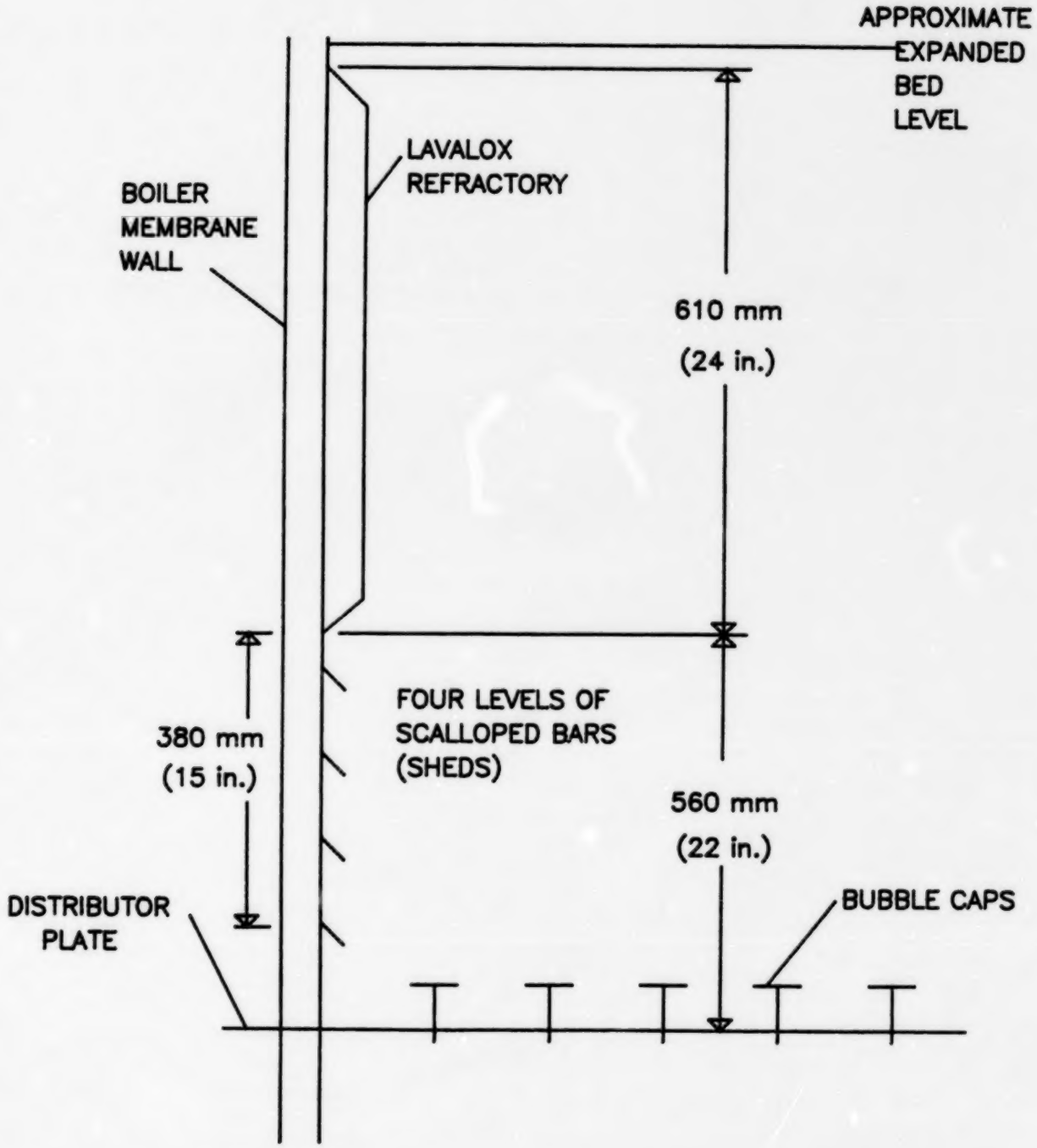


Fig. 4 - Schematic of refractory and scalloped bars applied to membrane walls

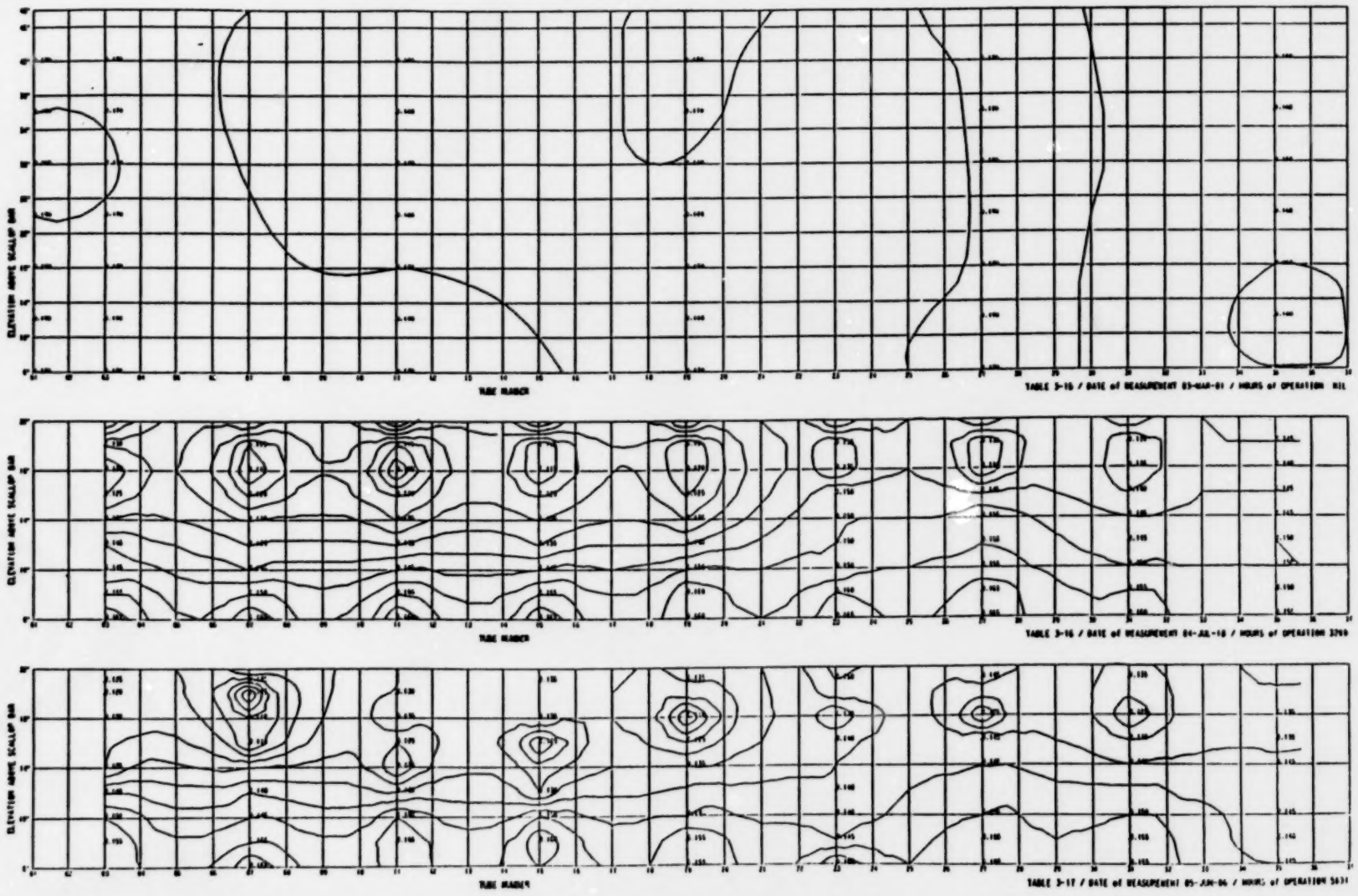


Fig. 5 - Annual contour plots of tube wall thickness for the drum wall of Boiler 2, Bed A

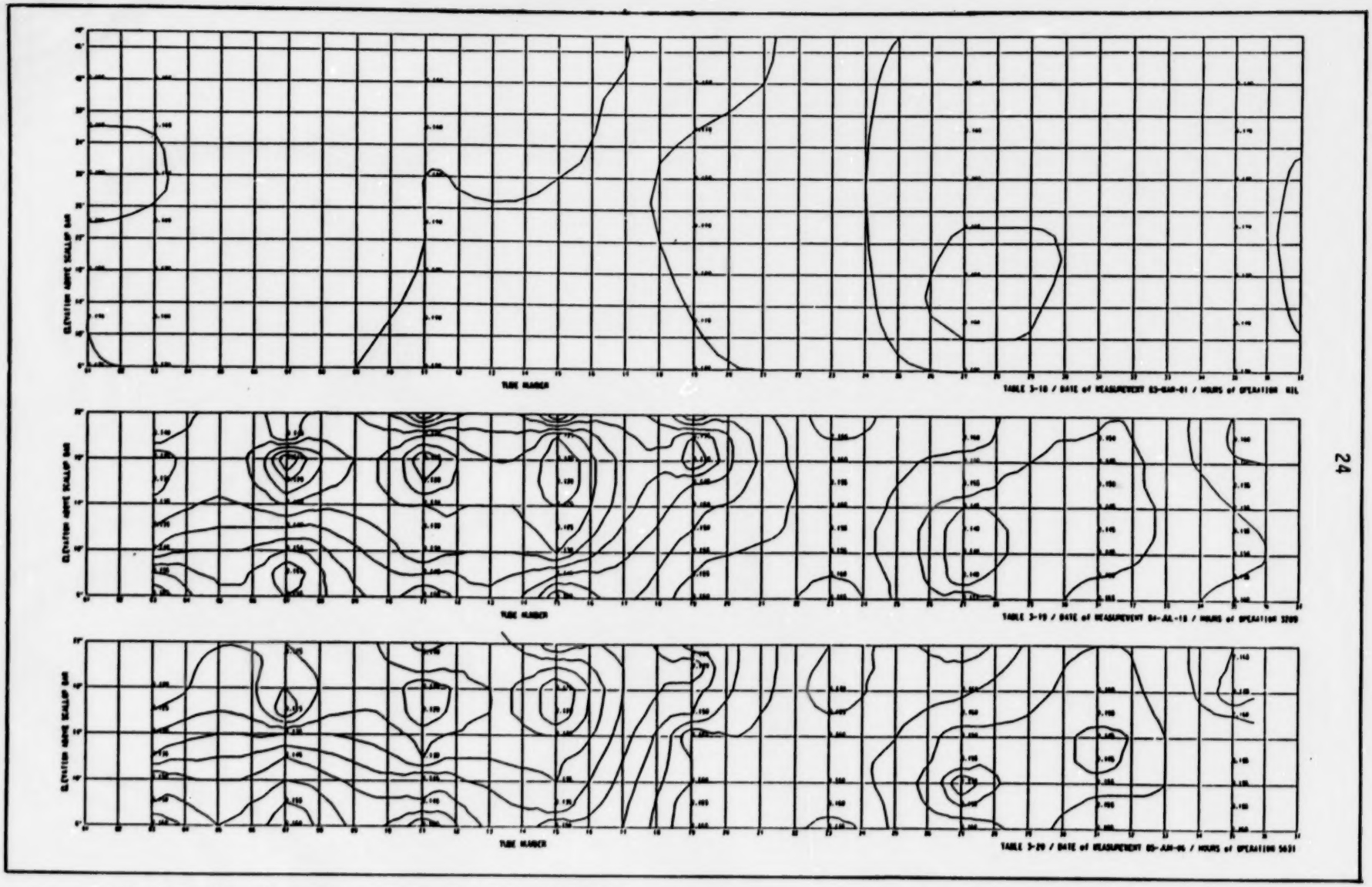
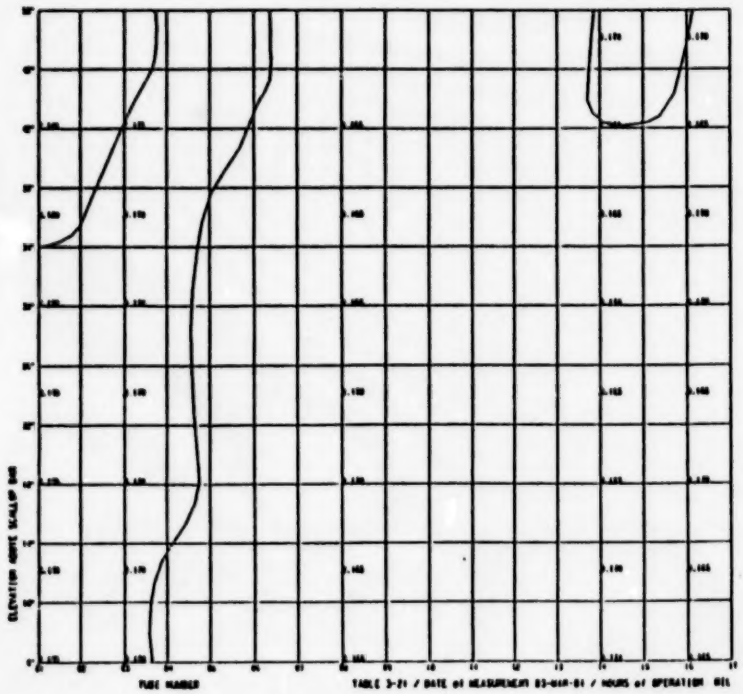


Fig. 6 - Annual contour plots of tube wall thickness for the partition wall of Boiler 2, Bed A



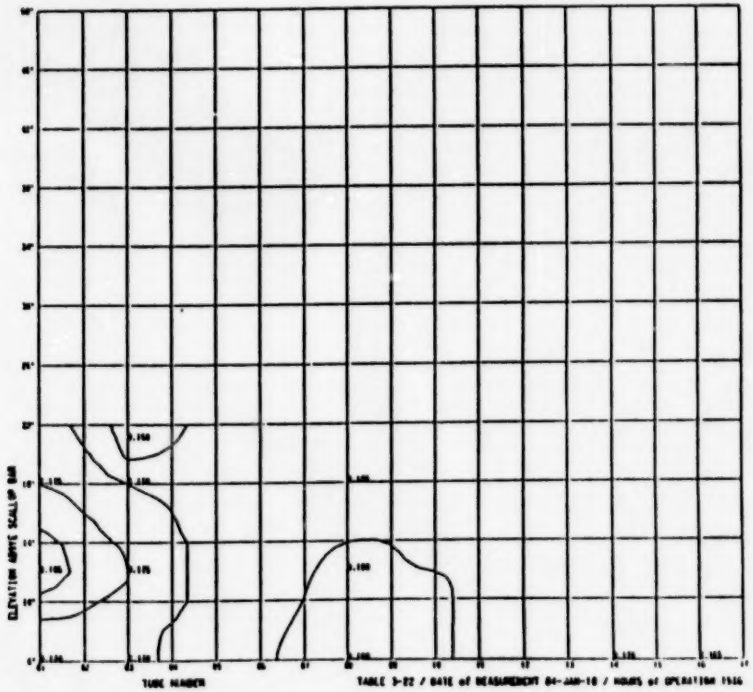


Fig. 7 - Contour plots of tube wall thickness for the stoker wall of Boiler 2, Bed A

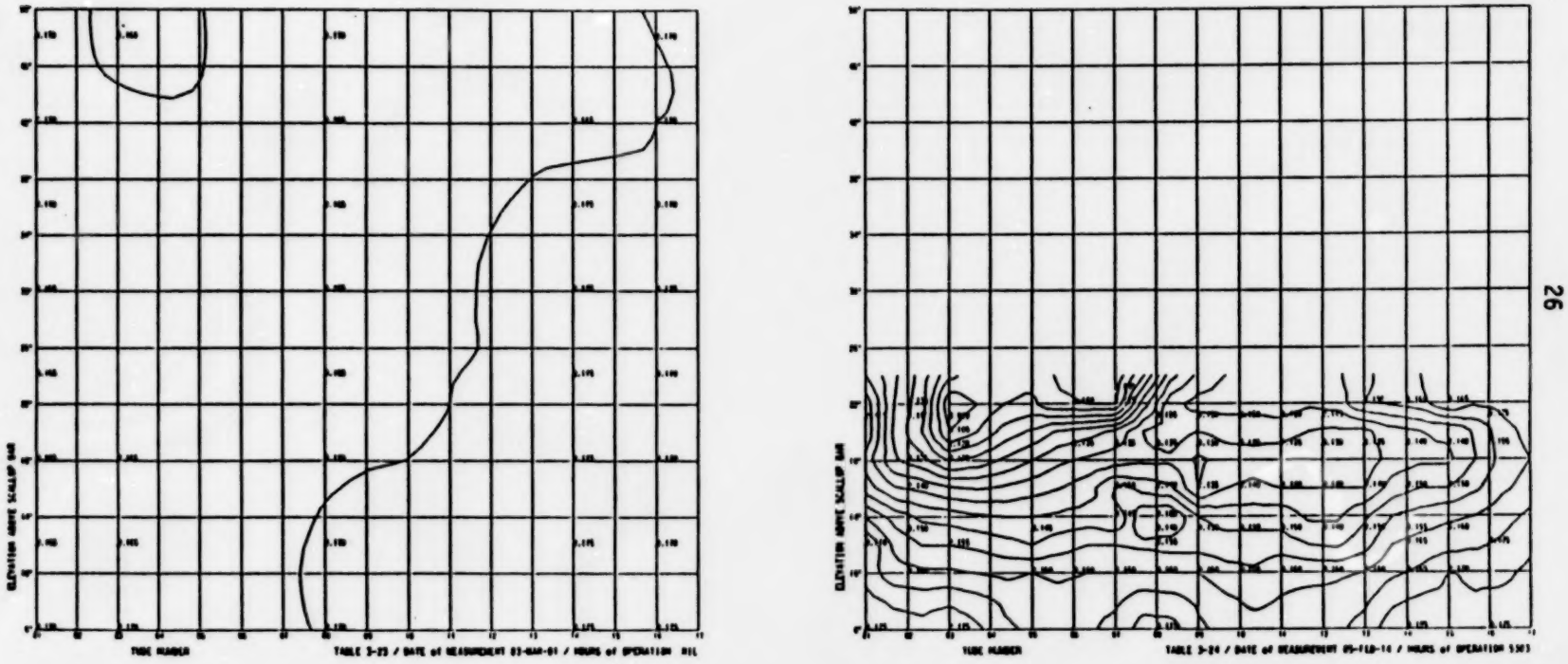


Fig. 8 - Contour plots of tube wall thickness for the sorbent injection wall of Boiler 2, Bed A

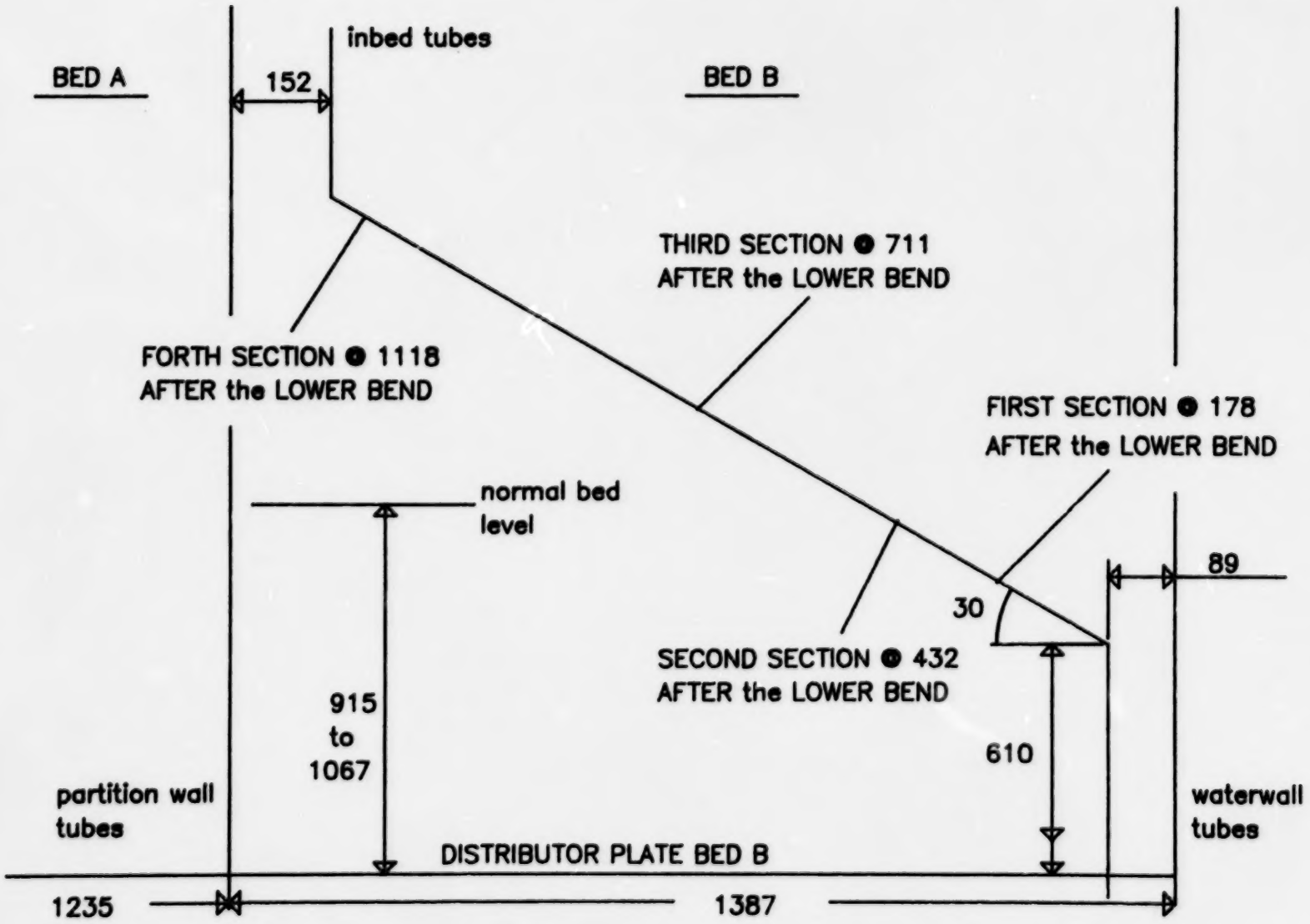


Fig. 9 - Dimensions (mm) and section locations of the original inbed tubes

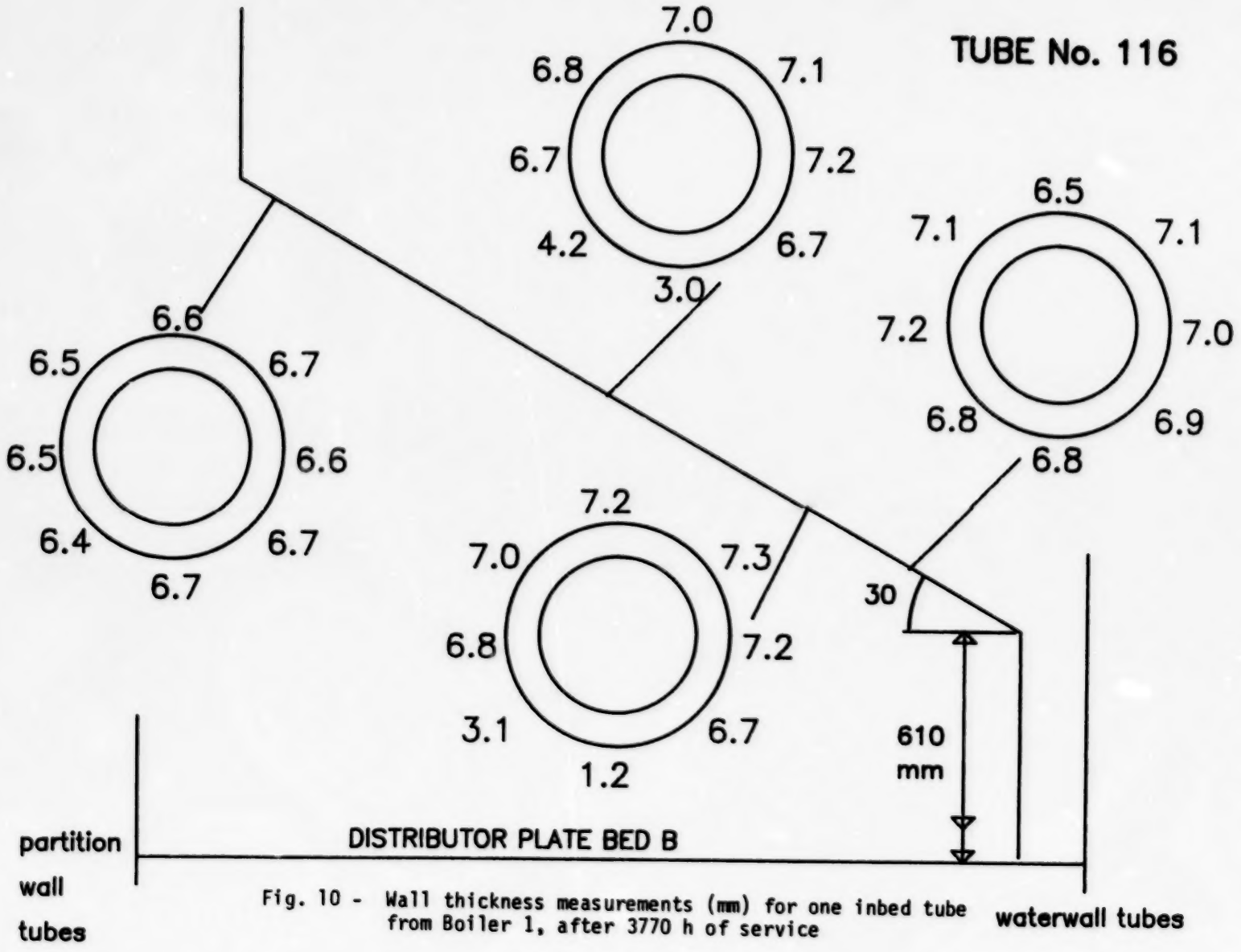
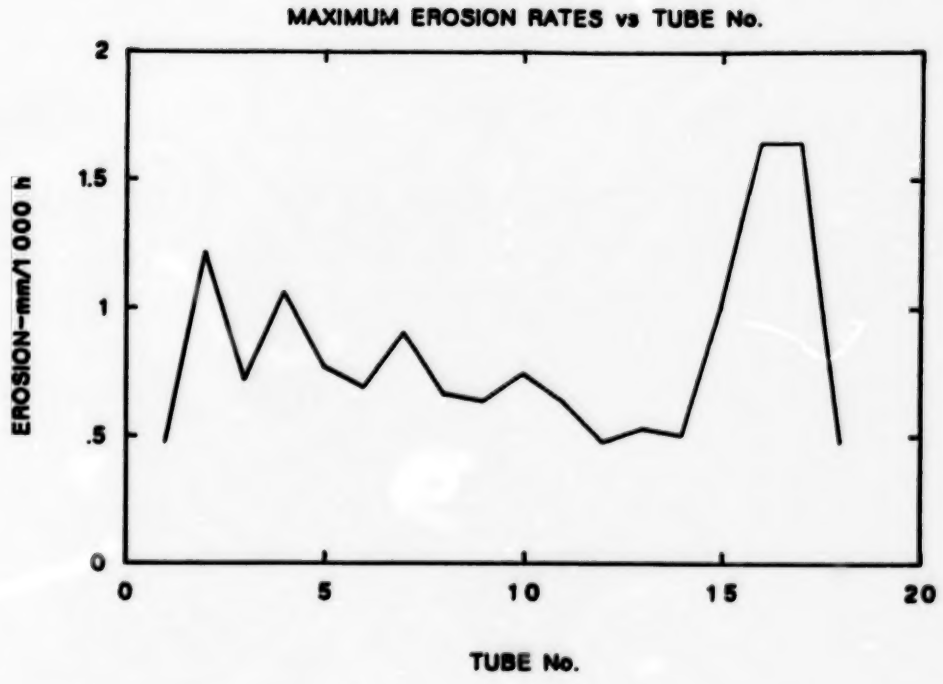


Fig. 10 - Wall thickness measurements (mm) for one inbed tube from Boiler 1, after 3770 h of service



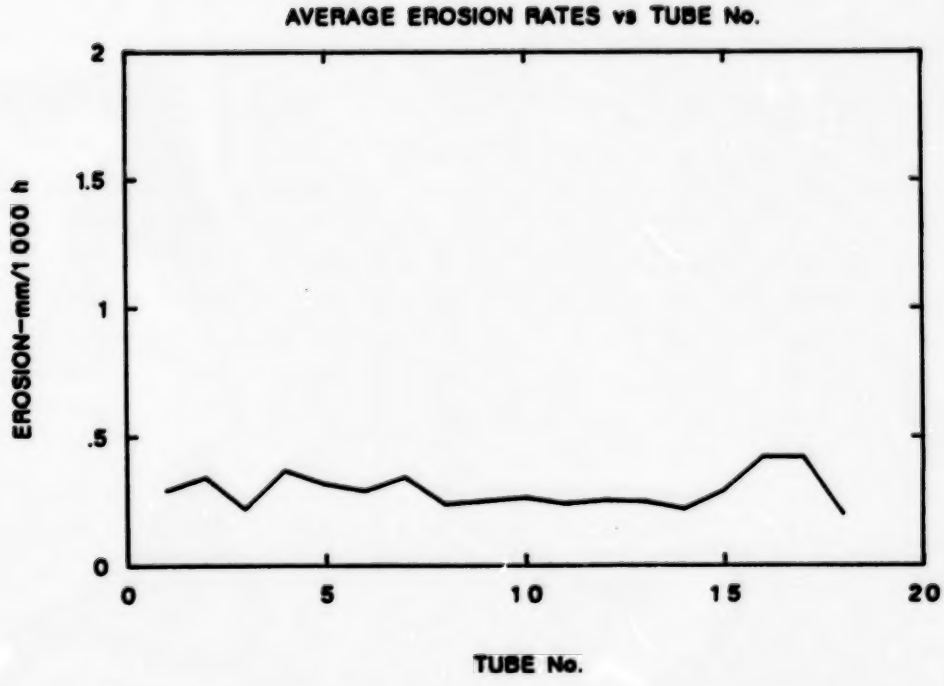
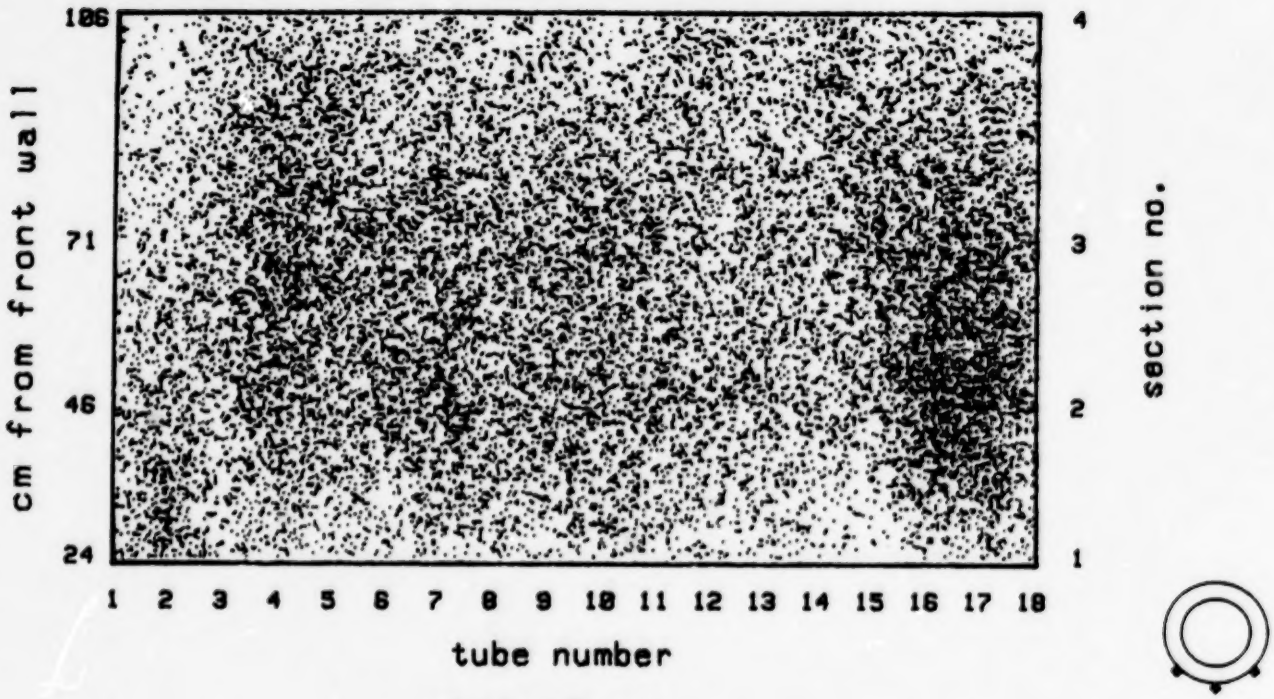


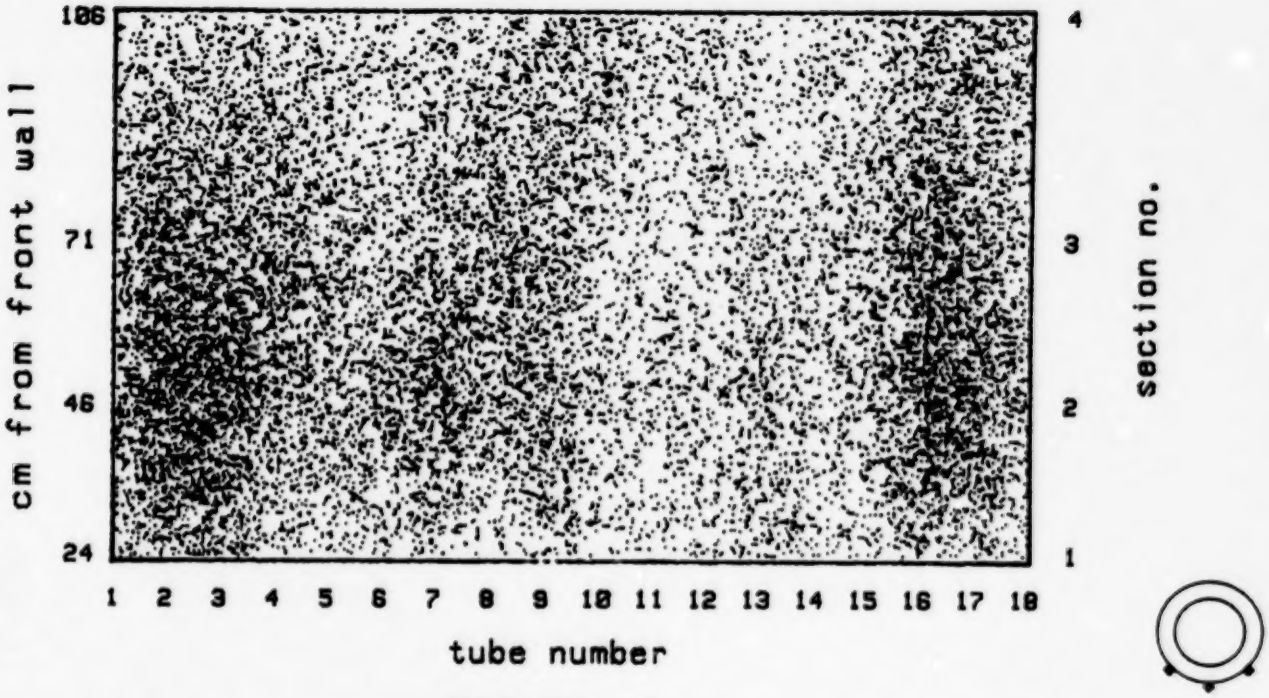
Fig. 11 - Maximum and average erosion rates for the inbed tubes from Boiler 1 after 3770 h of operation



BOILER 1

Tube #	RATE (mm/1000 h)				Tube #	RATE (mm/1000 h)			
	1	2	3	4		1	2	3	4
1	.04	.17	.17	.19	10	.33	.49	.59	.09
2	.79	.50	.28	.01	11	.18	.44	.38	.28
3	.11	.35	.42	.28	12	.11	.45	.30	.37
4	.27	.66	.69	.34	13	.12	.38	.43	.23
5	.19	.48	.64	.36	14	.04	.33	.41	.37
6	.10	.51	.52	.15	15	.05	.39	.67	.12
7	.27	.64	.56	.31	16	.15	.99	.73	.21
8	.23	.44	.46	.13	17	.26	.99	.74	.19
9	.11	.46	.47	.34	18	.10	.13	.25	.14

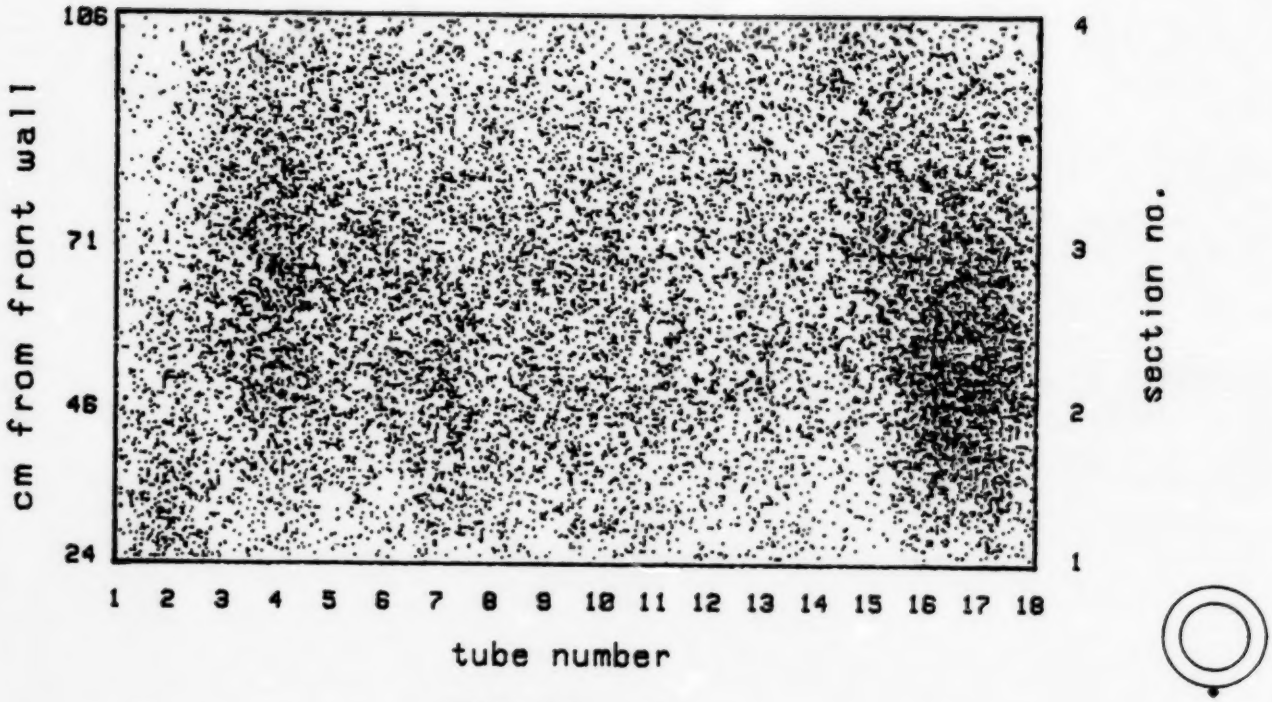
Fig. 12 - Erosion rates and distribution for inbed tubes from Boiler 1 after 3770 h of operation, average of three bottom measurements



BOILER 2

Tube #	RATE (mm/1000 h)				Tube #	RATE (mm/1000 h)			
	1	2	3	4		1	2	3	4
1	.07	.19	.21	.07	10	.07	.17	.10	.30
2	.37	.59	.49	.10	11	.06	.17	.08	.10
3	.34	.65	.39	.20	12	.12	.13	.10	.19
4	.14	.33	.31	.16	13	.22	.25	.10	.04
5	.16	.26	.26	.14	14	.09	.13	.16	.09
6	.12	.20	.16	.10	15	.14	.24	.23	.10
7	.17	.41	.25	.14	16	.23	.55	.47	.21
8	.01	.29	.30	.12	17	.17	.50	.30	.29
9	.17	.20	.26	.29	18	.06	.14	.09	.16

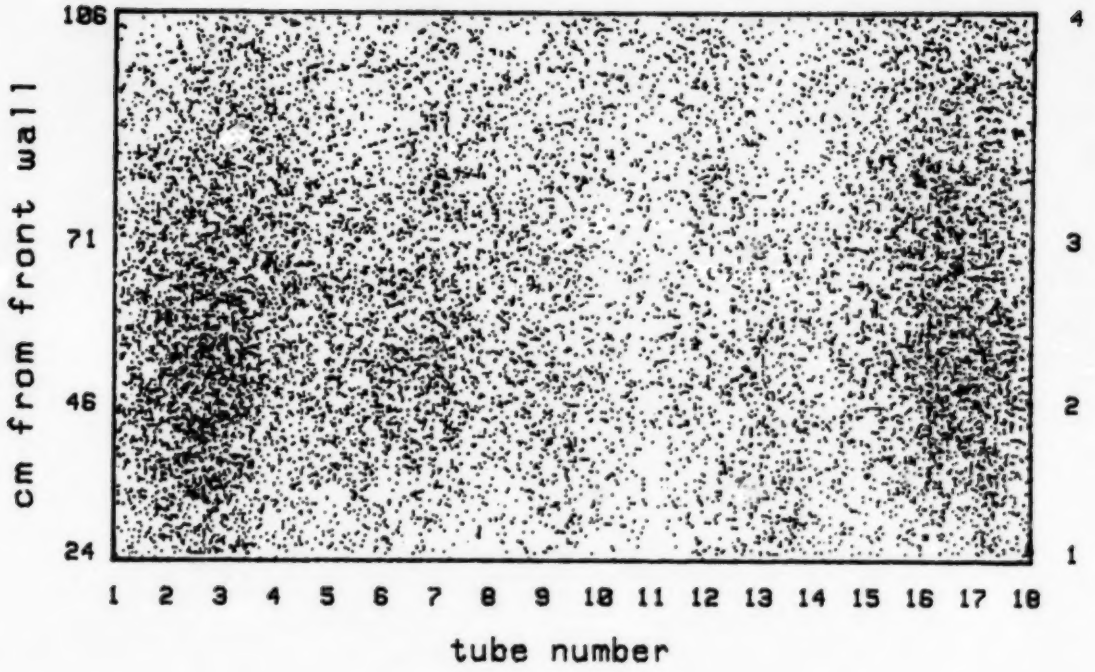
Fig. 13 - Erosion rates and distribution for inbed tubes from Boiler 2 after 3220h of operation, average of three bottom measurements



BOILER 1

Tube #	RATE (mm/1000 h)				Tube #	RATE (mm/1000 h)			
	1	2	3	4		1	2	3	4
1	0.0	.08	.03	.11	10	.40	.58	.74	.11
2	1.2	.50	.27	.03	11	.13	.64	.37	.37
3	.16	.53	.72	.42	12	.11	.48	.40	.53
4	.24	.93	1.1	.40	13	.13	.48	.53	.34
5	.08	.64	.77	.45	14	.08	.37	.50	.53
6	.13	.58	.69	.21	15	.08	.50	1.0	.34
7	.37	.90	.66	.29	16	.16	1.6	1.2	.19
8	.32	.58	.66	.13	17	.29	1.6	1.2	.19
9	.11	.64	.56	.37	18	.13	.16	.13	0.0

Fig. 14 - Erosion rates and distribution for inbed tubes from Boiler 1 after 3770 h of operation, measured at the bottom (6 o'clock) location



BOILER 2

Tube #	RATE (mm/1000 h)				Tube #	RATE (mm/1000 h)			
	1	2	3	4		1	2	3	4
1	.06	.19	.22	.06	10	.09	.22	.12	.28
2	.43	.71	.53	.03	11	0.0	.19	.09	.12
3	.47	.99	.65	.31	12	.12	.19	.19	.25
4	.16	.40	.47	.25	13	.31	.34	.19	.06
5	.16	.34	.34	.16	14	.16	.19	.19	.09
6	.16	.47	.28	.12	15	.16	.31	.31	.19
7	.09	.47	.40	.16	16	.16	.62	.62	.28
8	0.0	.25	.25	.12	17	.25	.78	.53	.34
9	.16	.31	.28	.12	18	.09	.09	.06	.16

Fig. 15 - Erosion rates and distribution for inbed tubes from Boiler 2 after 3220 h of operation, measured at the bottom (6 o'clock) location

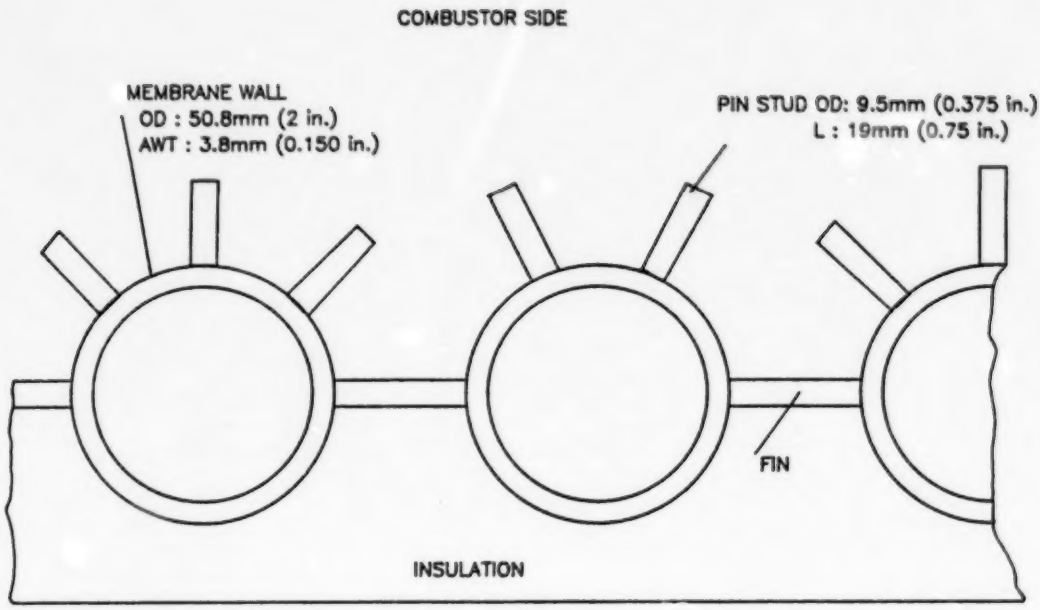


Fig. 16 - Arrangement of pin studs applied to waterwalls as an erosion protection measure

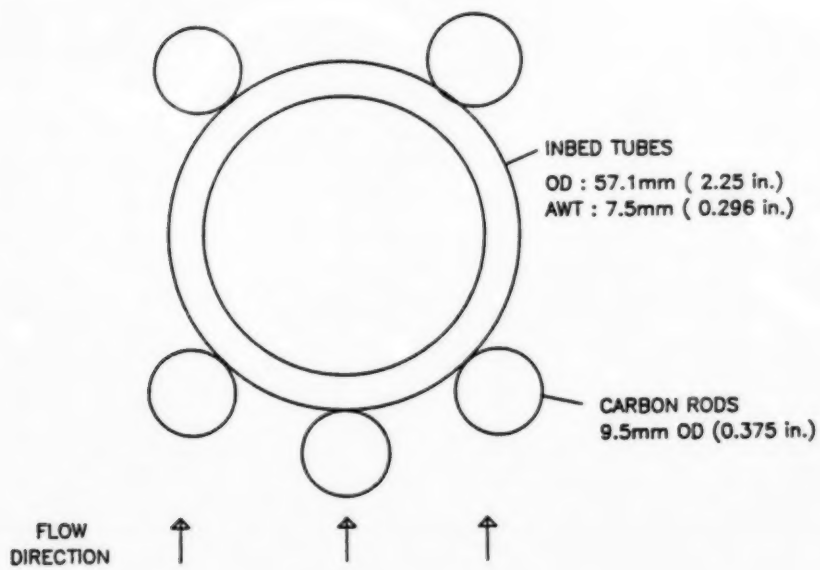


Fig. 17 - Location of the carbon steel rods welded to the inbed tubes as an erosion protection measure

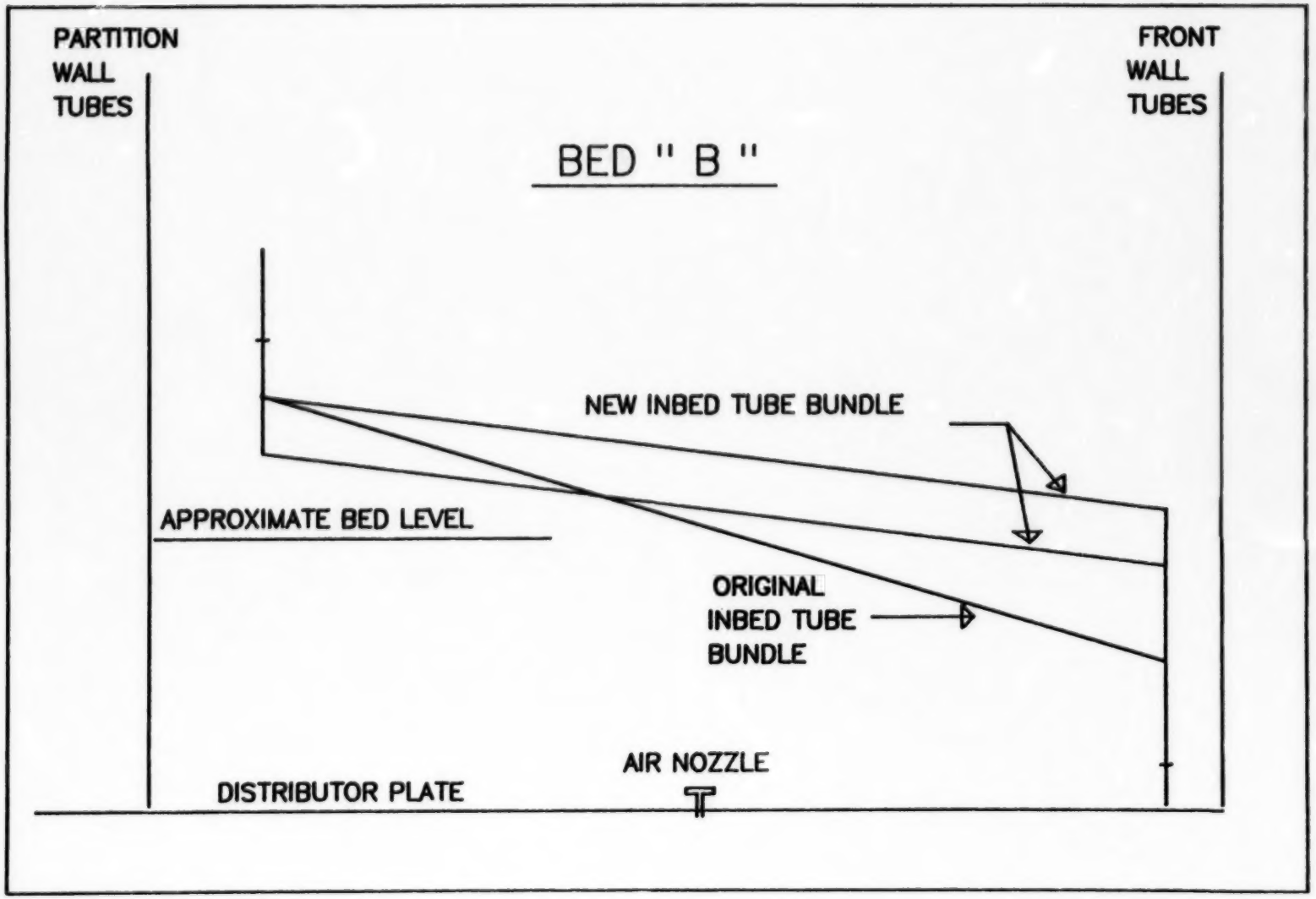


Fig. 18 - Configuration of the new inbed tube bundles installed in 1986

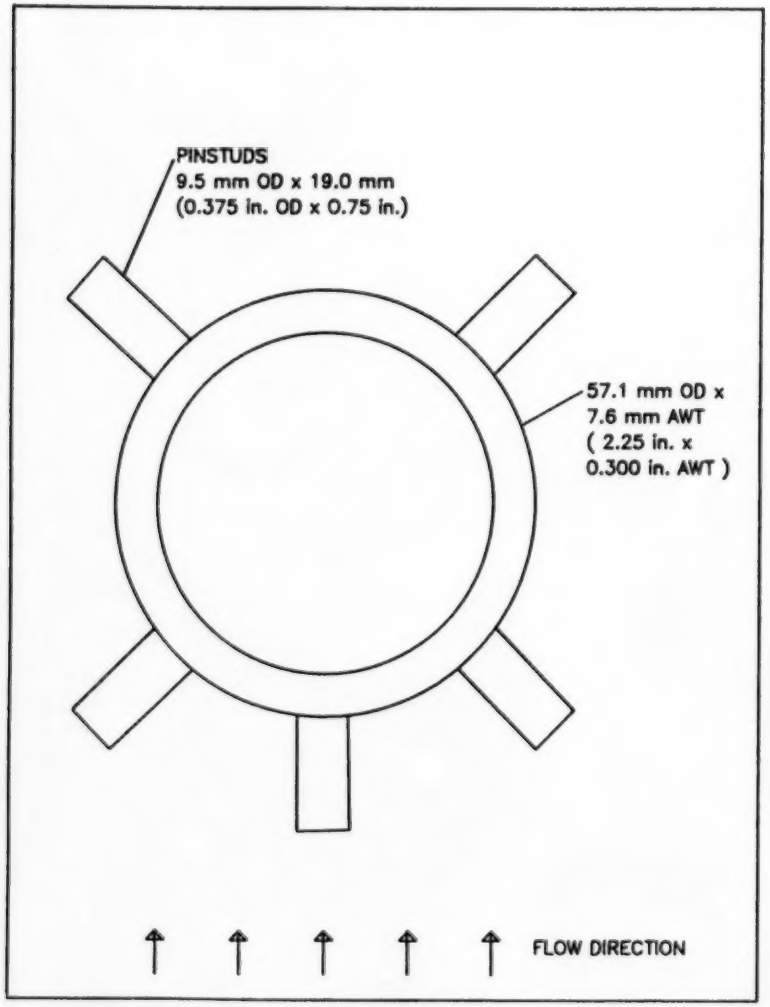


Fig. 19 - Orientation of pin studs applied to 6 tubes of the new bundle installed in Boiler 2 in 1986

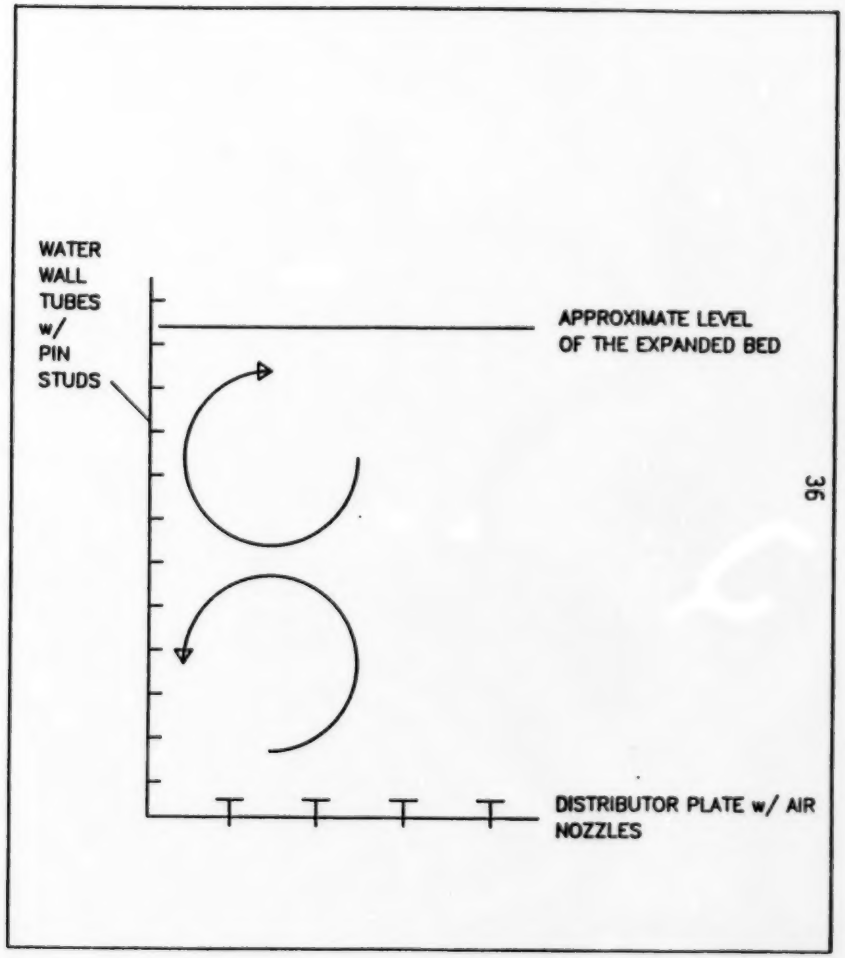


Fig. 20 - Bed flow patterns inferred from erosion patterns on the pin studs in the preferential beds